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# MECHANISM OF FLASH IN THE FLOW OF REFRIGERANT IN A CAPILLARY<sup>1</sup>

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## ABSTRACT

Flash delay (non-equilibrium phenomenon) occurred in refrigerant flow in a capillary affects apparently the prediction accuracy of refrigerant flow rate in a capillary. "Combined nucleation" theory that accounts for both "homogeneous nucleation" and "wall nucleation" was developed, based on which, a flash flow model was established. Underpressure, an important parameter reflecting non-equilibrium phenomenon in a capillary, was obtained with this flash flow model. The simulation results agree well with the experimental data. The results show that underpressure increases with increase of the mass flow rate of refrigerant and also increases with decrease of inlet temperature.

**Keywords:** capillary flash flow nucleation model

## NOMENCLATURE

A, B : Coefficient

$C_0$  :distributing parameter

$Cp_l$  : Isobaric specific heat

$d$  : diameter

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$f$ : Friction coefficient	$h_0$ : stagnant enthalpy
$h_{lv}$ : Potential heat	$j$ : velocity of the central volume
$K_s$ : Spherical correcting factor	$N_b$ : local bubble number density
$p$ : Pressure	$R_b(t)$ : radius of bubble
$t$ : Time	$T$ : temperature
$\bar{u}_b$ : Local velocity vector bubbles	$u$ : velocity
$x$ : Quality	$z$ : situation
$\rho_{v0}$ : Initial bubble density	$\rho$ : density
$\lambda$ : Conductivity	$u_{vj}$ : local shift flow velocity
$\alpha$ : Void fraction, diffusivity	$\Delta p$ : underpressure
$\Gamma_v$ : Evaporation rate	$\phi_{so}$ : bubble source
$\phi_{si}$ : Bubble sink	

### subscript

$b$ : bubble	$l$ : liquid
$s$ : saturation	$v$ : vapor
$0$ : initial state	

## INTRODUCTION

There exists thermal non-equilibrium phenomenon in the flow of refrigerant liquid in a capillary, which affect the prediction accuracy of mass flow rate apparently (Alamgir and Lienhar's result). Just for this thermal non-equilibrium of the refrigerant liquid, refrigerant liquid will flash in the capillary, the flash process is a process of bubble arising and growing. The key problems to study the flash process are how to establish bubble number density model and bubble growing model and how to relate micro parameters such as bubble number and bubble size to the macro parameters such as void friction, pressure and temperature. But so far, references related to bubble generation and bubble growing is aimed at the boiling of water at constant pressure or flash evaporation of water in a decompression condition, not account for the refrigerant bubble arising and growing in a capillary.

Aiming at the flash flow process of refrigerant in a capillary, the process of the bubble arising and growing is be studied in this paper. The relation of underpressure to bubble number density and bubble size area established to explore the mechanism of non-equilibrium phenomenon existing in a capillary and to study the effect of inlet conditions on the key parameter---underpressure.

## MATHEMATIC MODEL

### Bubble Number Density Model

The bubble transportation equation in the flash flow process is provided by Kocamustafaogullari et al:

$$\frac{\partial N_b}{\partial t} + \nabla(N_b \bar{u}_b) = \phi_{so} - \phi_{si} \quad (1)$$

where  $\phi_{so}$ 、 $\phi_{si}$  and  $\bar{u}_b$  respectively represent bubble source for bubble arising, bubble sink for bubble combination and local velocity vector of bubbles;  $N_b$  is local bubble number density.

For the stable flow in a capillary with constant section area, it is assumed that the first bubble arises at the saturation point  $z_s$ , integrating equation (1) from the saturation point  $z_s$  to point  $z_1$ , the bubble transportation equation for flash flow of refrigerant in a capillary can be derived as

$$N_b(z_1) = \frac{1}{u_b(z_1)} \int_{z_s}^{z_1} (\phi_w + \phi_{ho} + \phi_{he} - \phi_{si}) dz \quad (2)$$

where  $\phi_w$  is the wall nucleation source, adopting perimeter average value;  $\phi_{ho}$ ,  $\phi_{he}$  and  $\phi_{si}$  respectively represent homogenous nucleation source, heterogeneity nucleation source and sink for bubble combination, adopting area average value;  $u_b(z_1)$  is velocity of bubbles at the point  $z_1$ , adopting mass average value,  $N_b(z_1)$  is the bubble number density at point  $z_1$ , which account for the contribution of all the bubbles generated in the upstream to the bubble number density at point  $z_1$ , Equation (2) combined the effects of wall nucleation, homogenous nucleation, heterogeneity nucleation and bubble combination on the bubble number density, not only account for one of the above aspects, Wu and Cao developed “combined nucleation” theory according to the above equation.

A new parameter  $n_b(z_1, z)$  is introduced to express the contribution of the bubbles generated at the point  $z$  and arriving at the point  $z_1$  to the bubble number density at the point  $z_1$ :

$$n_b(z_1, z) = \frac{\phi_w(z) + \phi_{ho}(z) + \phi_{he}(z) - \phi_{si}(z)}{u_b(z_1)} \quad (3)$$

### Bubble Growing Model

It is assumed that liquid temperature at the liquid-vapor interface equals to vapor temperature and vapor temperature equals to saturation temperature corresponding to local pressure. The effects of gravity and surface tension are ignored. Cao derived the average radius of bubbles from the energy equation and mass equation:

$$R_b(t) = \left( \frac{\rho_{v0}}{\rho_v} \right)^{1/3} \left\{ - \frac{2K_s \lambda_l (-Y)^{3/2}}{\rho_{v0} h_{lv} \sqrt{\pi a_l}} \int_0^{Y_t} e^u (Yt - u)^{1/2} \cdot du \right\} \quad (4)$$

$$Y = \frac{fu^3 \rho_l (2T_l - B)}{dB \exp \left( A - \frac{B}{T_l} \right)} \quad (5)$$

where  $R_b(t)$  is the average radius of bubbles at time  $t$ ;  $\rho_{v0}$ ,  $\rho_v$ ,  $\rho_l$ ,  $\lambda_l$ ,  $\alpha_l$  and  $h_{lv}$  represent respectively initial vapor density, vapor density, liquid density, liquid conductivity, liquid diffusivity and potential heat;  $K_s$  is spherical correcting factor;  $f$  is friction coefficient;  $d$  is diameter of the capillary;  $u$  is velocity of refrigerant;  $T_l$  is liquid temperature; A and B is a constant related to physical property.

## Flash Flow Model

Void fraction and average velocity of bubbles can be calculated with the bubble number density model and bubble growing model established above. The void fraction  $\alpha(z_1)$  at  $z_1$  is ratio of all of the bubbles generated in the upstream of the point  $z_1$  and arriving at  $z_1$  at the same time to the inner volume of the capillary per unit length, and can be calculated by:

$$\alpha(z_1) = \int_{z_s}^{z_1} \frac{4}{3} \pi (R_b(t))^3 n_b(z_1, z) dz \quad (6)$$

$$dz = u_b(z) dt \quad (7)$$

where  $n_b(z_1, z)$  is the contribution of the bubbles generated at the point  $z$  and arriving at the point  $z_1$  to the bubble number density at the point  $z_1$ ;  $u_b$  is the average velocity of bubbles.

In the above equation, the average velocity  $u_b$  is an unknown, and can be obtained from the mass equation of vapor that is:

$$\frac{\partial}{\partial t} (A \alpha \rho_v) + \frac{\partial}{\partial z} (A \alpha \rho_v u_b) = \Gamma_v A \quad (8)$$

where  $\Gamma_v$  is evaporation rate and the equation for volume flow rate is

$$\frac{\partial}{\partial z} (A j) = \Gamma_v A \left( \frac{\Delta \rho}{\rho_v \rho_l} \right) \quad (9)$$

where  $j$  is the velocity of the central volume and  $j = \alpha u_b + (1 - \alpha) u_l$ . In addition, the relative velocity can be obtained from the shift flow theory<sup>[5]</sup>

$$u_b = j + C_0 u_{vj} \quad (10)$$

where  $C_0$  is the distributing parameter,  $u_{vj}$  is local shift flow velocity, adopting area average value.

The void fraction  $\alpha$  and the average velocity  $u_b$  of bubbles at the point  $z_1$  can be obtained from the above equations. Velocity of liquid  $u_l$  can be obtained from mass equation:

$$\alpha \rho_v u_b + (1 - \alpha) \rho_l u_l = \rho_{l0} u_{l0} \quad (11)$$

And quality  $x$  can be expressed as:

$$x = \frac{1}{1 + \frac{1 - \alpha}{\alpha} \frac{\rho_l}{\rho_v} \frac{u_l}{u_v}} \quad (12)$$

Liquid enthalpy  $h_l$  can be obtained from energy equation:

$$h_l = \left[ h_0 - x \left( h_v + \frac{1}{2} u_v^2 \right) \right] / (1 - x) - \frac{1}{2} u_l^2 \quad (13)$$

where  $h_0$  is stagnant enthalpy, which can be calculated from liquid enthalpy and kinetic energy of the inlet liquid.

Liquid temperature  $T_L$  is:

$$T_l = T_s(p) + \frac{h_l - h_s(p)}{Cp_l} \quad (14)$$

where  $h_{lv}$  is potential heat;  $h_s(p)$ ,  $T_s(p)$  represent enthalpy and temperature of saturated liquid corresponding to pressure  $p$ ;  $Cp_l$  is isobaric specific heat.

According to the above equations, the pressure  $p$  and temperature  $T$  along the capillary can be obtained. And the important parameter, underpressure  $\Delta p$ , can be obtained from the distribution curve of pressure and temperature.

## RESULTS AND DISCUSSION

Figure 1 is the distributions of void fraction along the capillary, the abscissa is distance from the saturation point  $l_{sat}$ , the coordinate is void fraction  $\alpha$ . The void fraction  $\alpha$  is decided by the two factors: bubble number density and bubbles size. Void fraction  $\alpha$  is closed to zero in front of the point 0.15m as both bubble number density and bubble size are very small. But behind the point 0.2m, void fraction would increase rapidly as bubble number density increase rapidly and bubbles grow bigger.

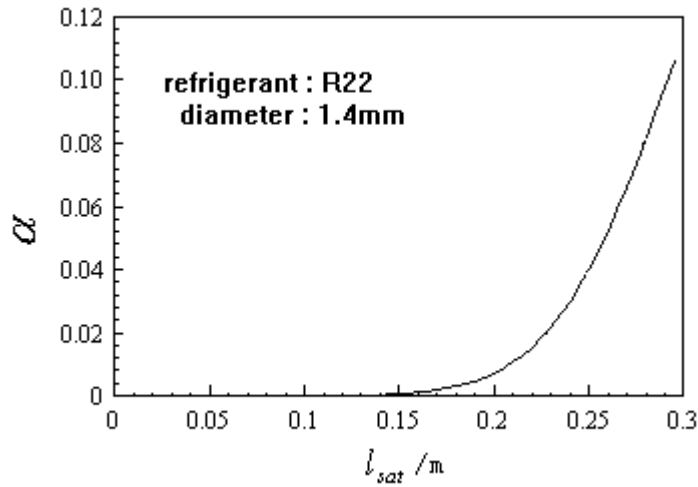


Figure 1 distribution of void fraction along capillary

Figure 2 is the distribution curve of the pressure and temperature in the bubble arising and growing region, the abscissa is the distance from the saturation point  $l_{sat}$ , the coordinate is the actual pressure and the saturation pressure responding to the temperature. The refrigerant is liquid ahead of the saturation point. Behind of the saturation point, the void fraction  $\alpha$  is very low till the point 0.21m from the saturation point (we recognize this point as turning point later), as figure 1 shown. But behind of the turning point, the temperature of the liquid would decline apparently; the curve of saturation pressure corresponding to the temperature would turn downward, at this time, the difference between the saturation pressure corresponding to the temperature and the actual pressure reaches the maximum value and which is defined as underpressure. In the downstream, temperature decrease in a relative high rate, and the superheat degree would become small gradually.

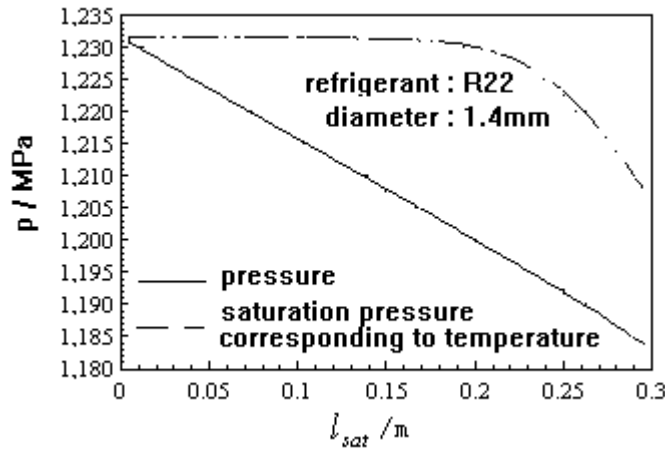


Figure 2 distributions of pressure and temperature along capillary

Figure 3 and Figure 4 are underpressure  $\Delta p$  versus mass flow rate  $\dot{q}_m$  and inlet temperature  $T_{inlet}$ . The results agree qualitatively with the experimental data that verified the flash flow model. The results shows that underpressure increases as mass flow rate increase and also increases as inlet temperature decrease. It can be expressed that: as the mass flow rate increase, the velocity increase, the distance for the bubbles to grow to a same size will elongate and the turning point of the temperature curve would be delayed, the pressure curve is related to the friction resistance which increases as the velocity increases, the pressure decreases in a relative high velocity, the pressure curve become a little steep, the actual pressure at the turning point of the temperature curve would be lower, as a result, underpressure would increase, and as inlet temperature decrease, the viscosity increase which makes the pressure curve become steep and surface tension of the liquid increase which make it difficult for the bubbles to departure from the wall, and the resultant bubble number density decreases, as a result, the turning point of the temperature curve would be delayed, and underpressure would also increases.

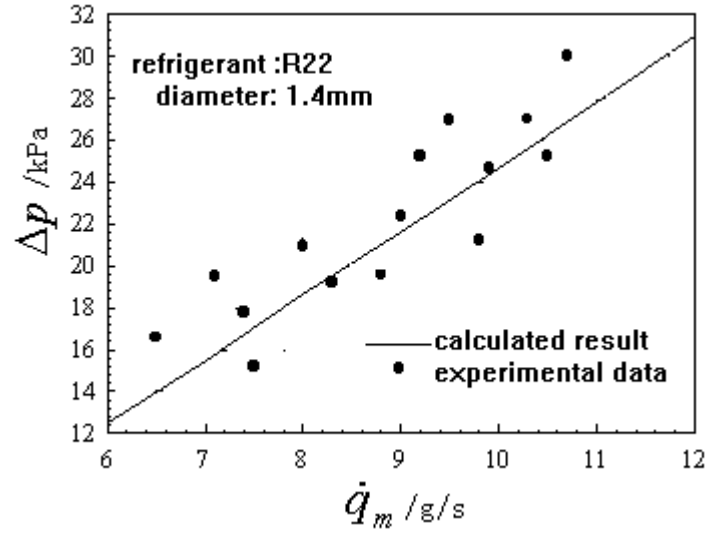


Figure 3 underpressure versus mass flow rate

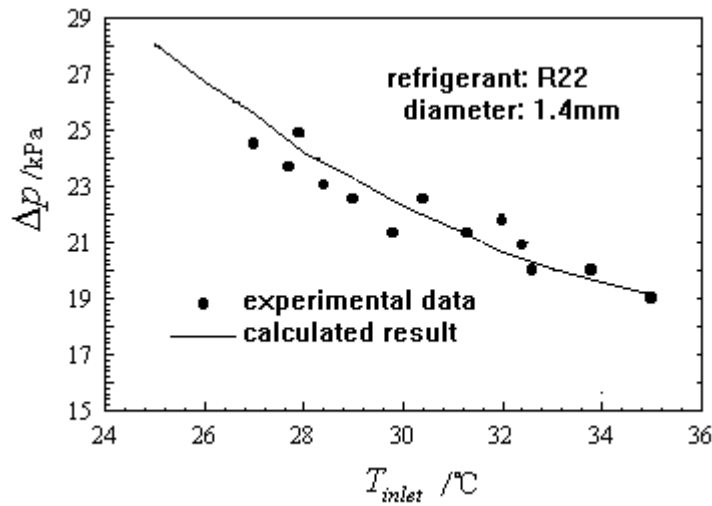


Figure 4 underpressure versus inlet temperature

## CONCLUSIONS

Flash delay (non-equilibrium phenomenon) occurred in refrigerant flow in a capillary affects apparently the prediction accuracy of refrigerant flow rate in a capillary. “Combined nucleation” theory which accounts for both “homogeneous nucleation” and “wall nucleation” was developed, based on which, bubble number density model, bubble growing model and flash flow model were established. Underpressure, an important parameter reflecting non-equilibrium phenomenon in a capillary, was obtained with this flash flow model. The simulation results agree qualitatively well with the experimental data, which verified the models established in this paper. The results shows



that underpressure increases as mass flow rate increase and also increases as inlet temperature decrease.

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